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STUDIES OF AURAL NONLINEARITY AND THE MECHANISMS OF AUDITORY FATIGUE

Annual Summary Report

by

JOHN ERDREICH

1 September 1979

Supported by

U.S. ARMY MEDICAL RESEARCH AND DEVELOPMENT COMMAND

Fort Detrick, Frederick, Maryland 21701

Contract No. DAMD 17-78-C-8074

Department of Otorhinolaryngology
University of Oklahoma Health Sciences Center
Oklahoma City, OK 73190

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A study relating individual differences in certain auditory and physiological parameters to individual susceptibility to auditory threshold shifts has been started. This report describes progress from 1 October 1978 to 13 July 1979. The initial parameter under study was auditory amplitude nonlinearity. However, in the process of the investigation, examination of the data suggested that tobacco smoking habits might be a confounding variable and this was investigated separately. The preliminary data suggest that smoking does predispose the individual to higher fatigued threshold shifts. Data at 1KHz suggest a relationship between amplitude non-linearity and threshold shifts. The results at 500 Hz and 2KHz are less clear. Reasons for this are discussed. Additional data must be acquired and analyzed before the relation between nonlinearity and impulse and continuous noise-induced TTS can be fully evaluated.

ABSTRACT

A study relating individual differences in certain auditory and physiological parameters to individual susceptibility to auditory threshold shifts has been started. This report describes progress from 1 October 1978 to 13 July 1979. The initial parameter under study was auditory amplitude nonlinearity. However, in the process of the investigation, examination of the data suggested that tobacco smoking habits might be a confounding variable and this was investigated separately. The preliminary data suggest that smoking does predispose the individual to higher fatigued threshold shifts. Data at 1KHz suggest a relationship between amplitude non-linearity and threshold shifts. The results at 500 Hz and 2KHz are less clear. Reasons for this are discussed. Additional data must be acquired and analyzed before the relation between nonlinearity and impulse and continuous noise-induced TTS can be fully evaluated.

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I. Summary

This study is concerned with factors influencing individual susceptibility to temporary noise induced threshold shift (TTS). The report covers progress during the period 1 October 1978 to 13 July 1979. Initially, the goal of the investigation was to examine the relation between the non-linear amplitude response of the ear and susceptibility of an individual to TTS. The rationale behind this approach was that optimum protection of people from noise hazard should include some yet unknown factor relating to the individual differences in sensitivity to permanent and temporary threshold shifts. Furthermore, if such a factor could be demonstrated, costs of hearing conservation programs incorporating such factors might be greatly reduced in comparison with programs which rely primarily on noise-reduction and hearing evaluation. In the course of the study it appeared that a few individuals exhibited relatively high TTS to fatiguing stimuli of 90-95 dB SPL. There were no obvious differences such as eye color or pigmentation between these listeners and the other volunteers. Further consideration revealed that the "high TTS" listeners were chronic tobacco smokers. For this reason, a short study was implemented to compare TTS susceptibility of smoking and non-smoking males. Data gathered so far supports the initial observation that the smokers generally exhibit higher TTS in response to a fatiguing tone than do non-smokers.

Comparisons on one observer indicate that abstention from smoking overnight results in reduced TTS comparable to that of non-smokers. This might suggest that one simple low cost action to reduce noise induced hearing loss is to aggressively prohibit smoking in noise hazard areas. Obviously this must be examined more carefully. The time course of sensitization and de-sensitization by cigarette smoke needs to be detailed as do questions of accomodation and adaptation to the effects of tobacco.

Data collection of the first ten listeners in the study of TTS and non-linearity should be complete within three weeks. At this point, it is too early to fully discuss the relationship between the variables. However, the data for 1KHz fatiguing and to a lesser extent, 2 KHz fatiguing, support the relation between amplitude non-linearity and TTS susceptibility.

A library of computer programs has been developed to acquire and analyze data regarding the TTS and non-linearity parameters. From the experience of the first group of listeners, minor changes will be made to allow finer resolution in the TTS measures and reductions in time for data acquisition on the nonlinearity measure. This will make the procedures more easily applicable to large population screening.

II. Introduction

Specification of acceptable noise exposure limits is again experiencing change based on additional information regarding the offending stimulus. Past standards were based primarily on exposure level with passing acknowledgement of the role of exposure spectrum by specifying the type of sound weighting factor. Characteristics of the auditory apparatus were not included in determining exposure limits, although the ear is obviously differentially frequency sensitive.

The old pragmatic approach is changing. Price (1979) has demonstrated a clear role of exposure frequency effects in impulse noise induced threshold shift. Other studies are beginning to question the role of physiological factors, auditory and otherwise, in the problem of individual susceptibility (Thomas et al., 1979). Furthermore, a review of the recent literature (Ward, 1973) indicates that noise induced hearing loss (NIHL) is considered as a public health problem which may be analyzed with the same epidemiological techniques which have been successfully applied to other diseases. Unfortunately, most of the attempts to apply these techniques are concerned with evidence of hearing loss in association with a specific type of exposure (industrial machinery, small arms, F100 aircraft, etc.); they do not address the variables which are relevant to the cause of NIHL.

The great unresolved question remains, "why is the difference in susceptibility to NIHL so great between individuals?" At this time we may only speculate about the answer. It would seem that the nature of the toxic stimulus, the physiological structure of the individual receptor organ, and the overall health of the individual are all relevant. Some of these factors can only be studied in large populations, others are amenable to laboratory study.

The original intent of this study was to examine the relation of aural combination tones, thought to reflect mechanical overloading of the receptor organ, to the production of threshold shifts. A fortuitous series of observations led us to examine smoking as another related factor. The data have not been acquired over a period long enough to allow complete discussion of the relations between factors. However, it appears that smoking predisposes the individual to TTS.

III. Background

A. Nonlinearity and Overload

A characteristic property of a material (Miller and Doeringsfeld, 1962) is that it will deform in response to an applied force. The deformation and the force are related by a constant of proportionality (E) termed the modulus of elasticity. This relation is Hooke's Law. At some level of applied force, however, Hooke's Law becomes invalid and the force and resulting deformation are no longer directly proportional–the material is overloaded and the proportional limit is exceeded. The relation between the force (stress) and the deformation (strain) has become nonlinear.

Although attempts to relate stress/strain nonlinearities and fatigue have been examined in past years by other investigators (Lawrence and Blanchard, 1954; Lawrence and Yantis, 1957), technical problems inherent in these studies precluded the demonstration of any relationship. These problems were 1) the lack of an adequate psychophysical technique for the quantification of overloading or nonlinearity, 2) the erroneous use of the detection of the effects of the nonlinearity (threshold for best-beats) as an indicator of degree of nonlinearity, 3) the failure to relate degree of nonlinearity with TTS produced by a fatiguing stimulus although the relation of nonlinearity and fatigue was postulated, and 4) no formal theoretical framework existed within which the ramifications of changes in acoustic parameters (energy, amplitude, and duration) could be related to an effect upon the sensory organ. Research in audition and in biomechanics in the past 25 years has provided a sufficient

foundation upon which the original relations may again be studied with a reasonable expectation of successfully demonstrating the role of stress/strain nonlinearities in the production of auditory fatigue.

1. Nonlinearity in Biomaterials

Recent studies in biological materials have shown nonlinear responses to the amplitude of a stimulus. Dick, et. al., (1968) studying the arterial system of the dog quantified nonlinear vessel wall deformation by measuring frequencies produced by the distortion of the artery in response to two varying pressures applied to the vessel. They hypothesized that the nonlinear characteristics were related to the visco-elastic properties of the arterial wall.

In a report which closely followed, Apter and Marquez (1968) demonstrated that these nonlinear effects were related to the microstructure of the arterial walls; specifically, to the fibrous elastin and collagen components.

2. Relation to the Organ of Corti

Although it is not necessary that there exist analogous structures in the inner ear for the same mechanical principles of nonlinear stress/strain relationships to exist, there is some structural similarity. Iurato (1962) has examined the ultrastructure of the basilar membrane and reported (p. 1388) that the proteins of which the fibrillar structures of the basilar membrane are constituted exhibit properties similar to that of collagen.

Because of the analogs of structure, and because of the universality of the relation between stress and strain, it is reasonable to speculate that overdriving the inner ear is manifested by a nonlinear response to the incident sound.

Although the first direct study of behavioral measures of nonlinearity and the production of TTS has only recently been undertaken, (Cobb and Erdreich, 1976, to be reported in a later section), other factors dependent on mechanical characteristics of the Organ of Corti have been implicated in the production of auditory fatigue by other investigators as described in the following section.

B. Suggested Relations between Psychoacoustic Phenomena and the Production of Auditory Fatigue

1. Factors other than Nonlinearity and Overload

Characteristics of the peripheral auditory function have been related to the production of auditory fatigue. Miller (1958) examined the relationship between masking and TTS level. He hypothesized that the "...intensity aspect of a defening stimulus should be represented by its masking effects rather than its spectrum level." His results did not strongly support the hypothesis. However, by giving increased weight to the signal-to-noise ratio within the critical band, he was able to show agreement between the parameters of masking at different frequencies

and TTS production. The best agreement between the data and his hypothesis was found by weighting the signal/noise ratio by a factor of 2.7. This is similar to the factor of 2.5 by which Hawkins and Stevens' (1950) critical ratio estimates (which are signal/noise ratios) can be corrected to agree with direct measurements of critical bandwidth (cf. Scharf, 1970). Because critical bandwidth is related to the extent of mechanical excitation on the basilar membrane (Fletcher, 1940) and this is ultimately related to masking and thereby to TTS in Miller's report, it implies a role of the mechanical properties of the Organ of Corti in the production of temporary threshold shifts.

An additional implication of peripheral factors in the generation of TTS was suggested by Huizing (1948). He attempted to relate threshold shift with loudness and the phenomenon of recruitment. Although Huizing did not explicitly define the mechanism of his proposed relationship, other investigators have attempted to formalize the nonlinearity/loudness relationship. Wever (1949) directly related the effects of nonlinear amplitude characteristics and the loudness of a stimulus by suggesting that the overtones produced as a consequence of the nonlinearity represented a shunting of energy away from the place of maximum excitation by the stimulus. This effectively reduced the stimulus loudness. Additional evidence of a relationship was presented by Clack (1975, 1978) in which he was able to relate scaled attributes of loudness with aural nonlinearity.

If, as Huizing originally suggested, a relation between TTS and stimulus loudness does exist, its importance may be secondary to a primary relation between auditory fatigue and aural nonlinearity.

Asymptotic threshold shift (ATS) studies by Mills and Talo (1972) and by Carder and Miller (1972) may be directly relevant to the question of a nonlinearity–TTS relation. Asymptotic threshold shifts measured after cessation of long duration fatiguing stimuli increase at an accelerated rate with respect to the intensity of the fatiguing stimulus. This rate of increase approximates 1.7 dB for each decibel increase in fatiguing level. The rate of growth of fatigue is similar to the growth observed for first-order nonlinear distortion products (the harmonic a frequency 2f and the combination tone at frequency $f_l + f_h$) in the human. If auditory fatigue is a phenomenon proportional to overload, this type behavior is predicted.

2. Direct Suggestions of the Implication of Auditory Nonlinearity

Lawrence and Blanchard (1954), drawing analogy with mechanical systems, proposed that the threshold shifts were the result of overdriving the ear; that when the system is driven beyond its elastic limit its output is no longer proportional to its input. As the system is further overdriven, the level is approached at which permanent damage is produced. They reasoned that susceptibility to noise induced hearing loss might correlate with a low threshold of nonlinearity measured at stimulus levels well below those which cause damage.

This and following studies of aural overload suffered from certain deficiencies. Primary among these was the fact that the best-beats

paradigm for estimation of nonlinearity was difficult to employ with patients (Lawrence, 1958) and furthermore, it incorrectly estimated distortion product levels (Egan and Klumpp, 1951). Another problem concerned the precise quantities being examined.

Lawrence and Yantis (1957) related the onset of overload following exposure to a fatiguing stimulus with the amount of auditory fatigue. Unfortunately, the measurement of aural distortion products following the production of auditory fatigue discloses nothing about the processes which are responsible for the fatigue. Rather, it reflects only the effect of a threshold elevation on the detection of the products of aural overload. Three facts were missing to establish a relationship between amplitude nonlinearity and auditory fatigue.

Fatigue must be shown to have a mechanical component, a direct demonstration of nonlinear mechanical amplitude characteristics in the cochlea is necessary to relate the concept of overloading with experi mental observation, and a comparison of fatigue and pre-exposure measures of nonlinearity is necessary.

Recent studies of chinchillas exposed to damaging levels of sound showed short-term mechanical deformation. After exposure to 120 dB SPL 1 KHz tones for 15 minutes, Hunter-Duvar (1977) demonstrated collapse of patches of stereocilia. More interesting is the observation that after 24 hours, the stereocilia of the inner hair cells returned to normal. The same occurred for outer hair cells after approximately two days. This suggests that a mechanical component of TTS may be reasonably expected and furthermore, that TTS may be examined in the context of the physical deformations.

The second item was provided by Rhode i.. 1971. He showed that the basilar membrane exhibits nonlinear amplitude behavior at high (but physiological) stimulus levels thus relating behavioral measures of nonlinearity with physical parameters. Last, a demonstration of amount of fatigue and a measure of nonlinearity was provided by Drescher and Eldredge in 1974. These authors showed that a relatively greater susceptibility to threshold shift between chinchilla and guinea pig is accompanied by an earlier departure from linearity of the cochlear microphonic input/output function. Until our recent pilot study however, this type of relationship had neither been investigated behaviorally nor had it been presented quantitatively.

C. Impulse Noise Studies

While a considerable amount of information has been accumulated regarding the effects of continuous noise on the auditory system, comparatively little is known about auditory hazard from impulse exposures. The work that has been done has established one fact: in nearly every aspect of auditory fatigue (growth and duration and level, recovery, time-intensity trade-offs) listeners exhibit more individual variability to impulse exposures than to steady exposures.

The growth of TTS with variations in impulse peak pressure behaves somewhat differently than growth for steady state noise. For continuous noise

once an exposure level is reached which produces a measured TTS_2, further increases in exposure level will produce equal increments in TTS_2 (Ward, et. al., 1959).

For impulse exposures, however, most listeners manifest a Critical Level for impulse intensity below which little, if any, TTS is produced (McRobert and Ward, 1973; Ward, et. al., 1961). Exposures at intensities exceeding Critical Level may produce substantial fatigue and the TTS vs. impulse amplitude functions often exhibit an accelerated rate of growth above Critical Level (Ward, et. al., 1961).

As Ward, et. al., (1961) have reported, the value of Critical Level varies over a range of 20-30 dB between listeners. McRobert and Ward (1973) have recently suggested that an appropriate strategy for studying the effects of impulse exposures therefore is to expose listeners at the same levels with respect to Critical Level.

Effects of auditory nonlinearities may manifest themselves when acoustic impulses are added to a continuous noise pedestal. Hamernik, et. al., (1974) have reported that the effect (the amount of TTS) of combined steady plus impulse noise exposures is greater than the sum of the effects of each individual exposure alone. This finding relates to the demonstration of Ward, et. al., (1961) of the effect of changing peak level of the impulse and the exposure duration to maintain equal energy exposures.

Ward's study demonstrated (experiment 6) that there was an intensity effect which is independent of average energy. That is, increasing impulse level and decreasing duration resulted in a slight increase of TTS without an increase in exposure energy. Unfortunately, the authors reported administrative difficulties in examining the trading relations completely. Other difficulties in this type of study are attributable to problems of controlling impulse duration and level in a single transducer.

These two studies suggest that one factor which influences auditory fatigue produced by impulse noise exposures is the level of the exposure independent of exposure energy. If the fatigue is influenced by amplitude of the impulse as shown by Ward, et. al., the results of Henderson, et. al. can be explained in terms of a nonlinear amplitude effect.

If the factor relating TTS to impulse level is nonlinear, at high levels the amplitude effect is more prominent than at low. If the fatiguing effect of a stimulus is exponentially proportional to the signal amplitude, the effects of the sum of each alone is less than the effect of both simultaneously.

A second factor in TTS production is certainly exposure energy. As Fletcher and Loeb (1967) demonstrated, the number of impulses of short (36 msec) duration needed to produce a 20 dB TTS is greater than the number of impulses of longer (92 msec) duration to produce the same TTS. However, this study produced an intersting discrepancy in the reported results. The differences in impulse duration were aboutr 3:1 but the differences in number of impulses for equal TTS were between 4:1 and 7:1. Although differences in the power spectrum may be responsible for some of the discrepancies, it is tempting to speculate that the number/duration trading relationship is confounded by the role of amplitude factors in TTS production. Specifically,

because of nonlinear effects at higher stimulus levels, high level stimuli of short duration produce more threshold shift than low level long duration impulse of equal energy.

D. Relation of TTS and PTS

Generalization of auditory nonlinearity as a predictor of TTS to its use as a PTS susceptibility index is dependent on a direct relationship between TTS and PTS. Nixon, Glorig and Bell (1965) examined a group of workers exposed to noise of measured spectral complexity. They concluded that there was a significant correlation between PTS and TTS at all the frequencies they examined. These authors proposed the use of TTS as an adjunct test for determining individual hearing conservation criteria.

Although there may be a correlation between TTS and PTS, the nature of this relationship requires further scrutiny. As Miller, et. al., (1963) indicated, the frequency patterns of TTS and PTS are not necessarily the same for exposure to sounds of identical spectrum. Permanent sensitivity deficits from short high exposure may exhibit different characteristics than those from longer more moderate exposure levels. The role of exposure energy and exposure level is still not clear.

E. Preliminary Studies by this Investigator

Using recently developed techniques for the estimation of aural distortion products (Clack, 1967, 1968; Erdreich and Clack, 1972) we have measured nonlinear amplitude characteristics in three normal ears. For the preliminary study (Cobb and Erdreich, 1976) aural distortion product estimates at frequencies $2f_l + f_h = 3200$ Hz and $f_l + f_h = 2200$ Hz were determined with the tone-on-tone masking paradigm. Each of the listeners exhibited widely different levels of first-order ($f_h + f_l$) and of second-order ($2f_l + f_h$) distortion. Using a fatiguing stimulus of 1000 Hz and testing thresholds at 1400 Hz, the listeners were exposed to 80, 90, and 100 dB SPL tones for a period of twelve minutes. Both TTS_2 for each fatiguing stimulus and the rate of change of TTS_2 with fatiguing intensity were examined.

A relationship was found between second-order nonlinearity as evidenced by the level of the subjective tone $f_h + f_l$ and the level of TTS_2 at 100 dB. As the second-order nonlinearity is representative of asymmetric distortion such as might be expected from structure like the Organ of Corti, this supports the hypothesized relation between overload and TTS production. No relation was evident between either third order nonlinearity and TTS or between the rate of increase of TTS when exposure level was changed from 90 to 100 dB SPL.

F. Non-auditory prarameters of susceptibility

Among the many factors which have been suggested as relevant to NIHL susceptibility, those reflecting microcirculatory distrubances are repeatedly cited. As the result of observations that some of the listeners appeared to fall in a population of "high susceptability" ears, we tried to find a common factor between these listeners. Age, color, physical stature, all seemed unrelated. The only common trait was tabacco smoking habits.

In 1962 Muffei and Miani demonstrated vascular lesions in the cochlea of guinea pigs subacutely intoxicated and chronically exposed to tobacco smoke. Although certainly a plausible mechanism of auditory pathogenesis, we questioned whether alternative mechanisms might explain the differences in susceptibility to NIHL or if there is a real effect of smoking on susceptibility.

Bobbin and Gondra (1976) found that nicotine administration (both IV and intracochlear) had no demonstrable effect on hair cell loss and reticular lamina scarring in guinea pigs subjected to intense sound stimulation. Although this might be taken as evidence that nicotine is ineffective as a sensitizing agent, there is a body of literature in which smoking habits have been found to be related to hearing loss (Sieglaub, Friedman and Adour, 1974; Weiss, 1970). A problem with these studies, however, is that they are merely correlations. No information is available by which the mechanism of the effect may be defined. Is the role of nicotine important? Furthermore, they are retrospective, examining the habits of those individuals with known hearing loss. Nothing can be said about the involvement of nicotine or about its lack of importance. Habits of smokers which may predispose them to hearing loss cannot be separated from the effects of smoking itself; there is evidence which supports an involvement of autonomic component of the efferent innervation of the inner ear (Ross, 1971; Seymour and Tappin, 1953).

It is not implausible that autonomic effector agents such as nicotine have an effect on inner ear homeostasis. Other chemically mediated components of auditory fatigue have recently been postulated by Guth and his colloborators (1978). Suga and Snow (1969) have demonstrated increased cochlear blood flow in response to epinephrine and ephedrine. Norepinephrine elicited a transient decrease in cochlear blood flow. Although it is not clear if the mechanism of control is located in the cochlea or is secondary to changes in systemic circulation, the study does present evidence to support the relation between substances affecting autonomic function and hearing.

IV. METHODS

A. Subjects

Ten normal hearing ($\pm$10 dB HTL, ANSI 1969) male and female college students have been recruited as listeners to date. All listeners are screened at the beginning and end of the study with sweep frequency Bekesy audiograms. They are paid $1.35 per half-hour session during the conduct of the experiment and paid a bonus of $1.35 per session if they complete the study. Only one ear is tested in these subjects.

Nine male smokers and nine male non-smokers between the ages of 26 and 42 have been recruited for the smoking study.

B. Measurement of Auditory Nonlinearity

The observers are presented a monaural stimulus consisting of two continuous tones at frequency f_1 and f_2 and a pulsed tone at the frequency of the nonlinear distortion product f_{DP} being measured. The pulsed tone occurs in one of the two intervals in a (2AFC) forced choice paradigm. All

tones are synchronized with a common reference frequency. Acoustic distortion levels are at least 70 dB below the level of the primary tones to insure that acoustic artifacts do not contaminate the measurements.

As the phase of f_{DP} varies relative to the aural distortion product at the same frequency, the amplitude of the acoustic tone at f_{DP} necessary to reach threshold changes. From these threshold variations, the masked threshold and level of the aural distortion product may be determined with the algorithm reported by Erdreich and Clack (1972).

After calculating the aural distortion product level (L) and masked threshold, the coefficient of the appropriate term of the power-series nonlinearity may be computed as follows:

for the first-order sum tone $f_2 + f_1$ the level of this distortion is

$$L_{f_2+f_1} = a_2 p^2 \tag{1}$$

where p is the sound pressure of the stimulus and a_2, the coefficient of interest. Similarly, for the second order sum tone $2f_1 + f_2$

$$L_{2f_1+f_2} = 3a_3 p^3/4. \tag{2}$$

Rearrangement of the terms of these equations allows calculation of a_2 and a_3 as:

$$a_2 = L_{f_2+f_1}/p^2 \text{ and} \tag{3}$$

$$a_3 = 4\ L_{2f_1+f_2}/3p^3. \tag{4}$$

Coefficients of the second and third order terms of the power series (a_2 and a_3) are calculated for frequency regions as follows:

f_1 = 500 Hz	f_2 = 600 Hz	$f_{DP} = f_2 + f_1$ and $2f_1 + f_2$
f_1 = 2000 Hz	f_2 = 2400 Hz	$f_{DP} = f_2 + f_1$ and $2f_1 + f_2$
f_1 = 1000 Hz	f_2 = 1200 Hz	$f_{DP} = f_2 + f_1$ and $2f_1 + f_2$

The threshold measurements of f_{DP} are made with f_1 and f_2 masker levels of 70 dB SPL. Additional levels of 60 dB SPL and 80 dB SPL are used at f_1 = 1000 Hz f_2 = 1200 Hz to provide data relevant tothe change, if any, of a_2 and a_3 with intensity or the change of L_{DP} with intensity.

The tone-on-tone masking paradigm has been modified from that run in the past so that it is adapted for computer automation. A two-alternative forced choice paradigm employing a Levitt (1971) transformed UP-DOWN adaptive tracking procedure has been developed to supplant the Bekesy tracking procedure employed previously.

A tone at f_{DP} 500 msec in duration is presented within one of two 600 msec observation intervals separated by 100 msec. A light marks the observation interval. Primary tones at f_1 and f_2 are on continuously.

To reduce subjective response variability, response of "-" ("+" correct, "-" incorrect) will cause the stimulus level to be increased and responses of

"++" will cause the level to be decreased. This fixes all listeners' behavior on the upper portion p (correct) = 0.707 of the psychometric function relating stimulus level with response probability.

C. Measurement of Temporary Threshold Shift

1. Continuous Exposures

Fatiguing frequencies approximated the primary frequencies at which distortion estimates were obtained. Both pre- and post-fatigue thresholds are obtained with a Bekesy tracking procedure under control of the computer. Only the threshold at 1.4 times f_{exp} (the frequency at which maximum TTS is produced) is traced. This was necessitated by the duration of the pulsed tone and the time required to track threshold. Stimulus level changes at 3 dB/sec. Following determination of the pre-fatigue threshold, the fatiguing stimulus is turned on for twelve minutes at sound pressure level and frequency appropriate to one of the experimental conditions below. After twelve minutes, the fatiguing stimulus is turned off and recovery thresholds are obtained as outlined below. Threshold is traced at the test frequency for twelve minutes with data being recorded every 10 seconds.

Exposure conditions:

f_{exp} = 500 Hz @ 90 and 100 dB SPL

= 1000 Hz @ 90, 95, and 100 dB SPL

= 2000 Hz @ 90 and 100 dB SPL

f_{exp} = Octave band noise f_{center} = 500 Hz 90 and 100 dB_{BL}

= Octave band noise f_c = 1000 Hz 90 and 100 dB_{BL}

= Octave band noise f_c = 2000 Hz 90 and 100 dB_{BL}

TTS test frequencies:

$1.4\ (f_{exp})$

2. Impulse Exposure

Pre-exposure thresholds at 4000 Hz are determined with the tracking procedure as in the continuous exposure studies. Fatiguing stimuli are one-minute exposures to impulses of 500 sec duration initially at 140 dB peak SPL. Following cessation of the exposure threshold is measured at 4000 Hz and TTS thirty seconds post-exposure is compared with pre-exposure levels.

Impulse amplitude is increased in 3 dB increments until a TTS_{30sec} of 20 dB is produced. This defines the Critical Level for the impulse exposures. This data is not complete as of the end of the report period (13 July).

3. Subject Scheduling

One experimental condition is run each day.

D. Apparatus

1. Stimulus Generation

Signals of high spectral purity (distortion more than 70 dB below primary levels) are produced with low distortion oscillators. To preserve the purity of the signal, level changes are accomplished with passive programmable attenuators. All signals are fed to the attenuator at maximum amplitude.

Impulse stimuli are produced by a Hewlett-Packard 3300A generator. The output drives a McIntosh power amplifier feeding a modified Altec 808-88 driver. The driver is coupled directly to the ear with a short tube containing a B & K 1/8" microphone for waveform monitoring.

2. Calibration

Standard Bruel and Kjaer microphones and couplers are available for calibration of the continuous signals. All signals are measured with a General Radio 1900A wave analyzer.

Impulse stimuli will be monitored with an 1/8 inch condenser microphone at the external meatus within the matching section.

E. Effects of Smoking

Eighteen normal hearing males selected as above served served as listeners. their ages were between 26 and 42. Half were non-smokers and half smoked approximately one package (20 cigarettes) per day.

Susceptibility to TTS was determined as in the first section for 0.5, 1 and 2 K Hz fatiguers at 95 dB SPL for 12 min. Thresholds were measured at 1.4 times the fatigue frequency. Some additional measures were made at 2KHz, 90 dB SPL.

The two groups were examined for differences between mean TTS at each frequency and for differences in TTS as a function of their threshold at the test frequency.

V. RESULTS

A. TTS and Nonlinearity

The data collected through 13 July were examined for relationships between TTS and auditory nonlinearity. Considering the number of subjects completed, the analysis is descriptive only. Any formal mathematical analysis of factors related to TTS is reserved until data acquisition is more complete.

Initial data at 1000 Hz as illustrated in Figure 1 supports the findings of our pilot study that there is a relationship between the amount of quadratic nonlinearity at a stimulus level of 70 dB SPL and the TTS at 1.4 K Hz produced by a 100 dB SPL,

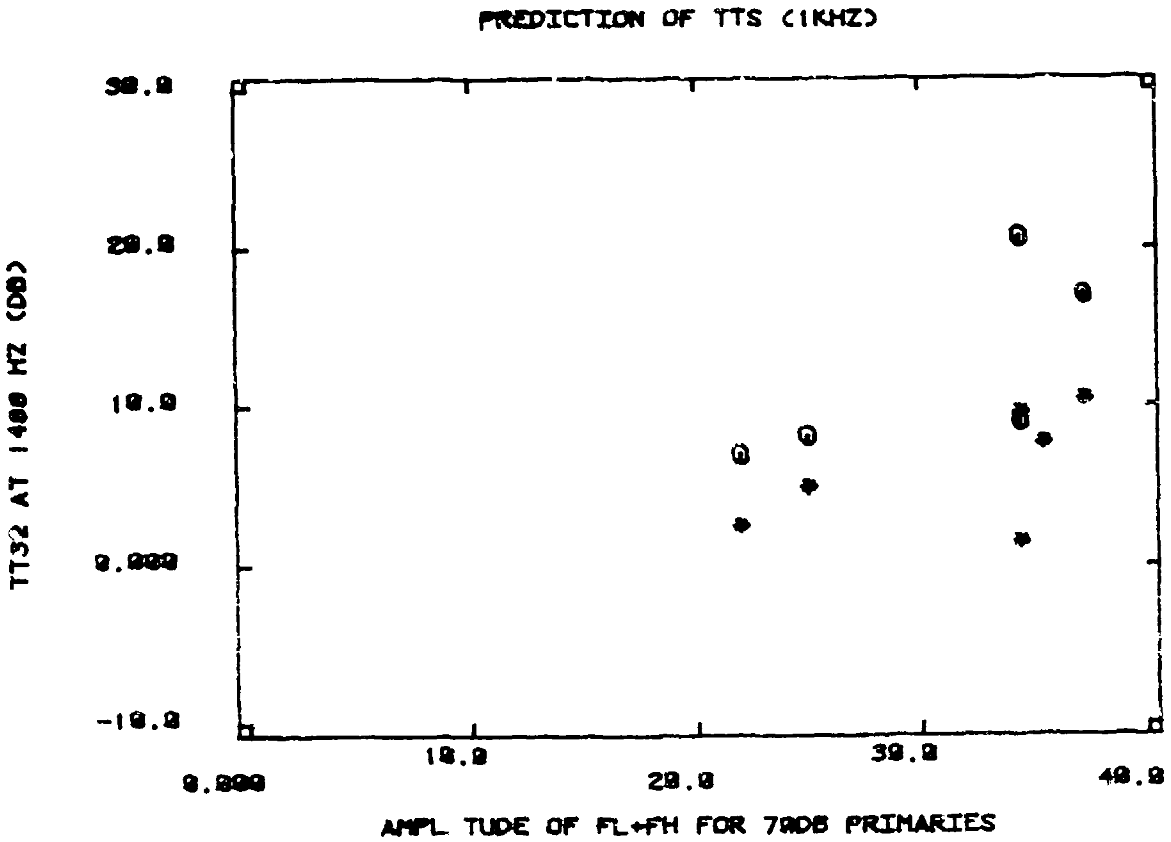

Figure 1: Relationship between aural nonlinearity (level of combination tone $f_1 + f_h$) and TTS_2 at 1KHz.

*90 dB SPL fatiguer
⊙ 100 dB SPL fatiguer

12 minute fatiguing tone at 1 K Hz. There is a similar relationship to fatiguing produced by a 90 dB SPL fatiguer. Each point in Figure 1 represents the distortion from a different listener plotted against the TTS produced in that subject by the 90 and 100 dB SPL fatiguers. Data represent averages of test/retest measures of combination tone amplitudes and TTS measures.

At 500 Hz fatigue levels are both similar for all listeners and generally low (less than 5 dB for a 90 dB fatiguer and less than 8 dB for a 100 dB fatiguer). Low TTS levels caused by low frequency tones has been reported before (Zakrisson, 1975) and is attributed in part to the protective mechanism of the aural reflex. In this case, one would not expect a predictive value of aural overload and, as illustrated in figure two, none exists. At 2000 Hz in response to a 90 dB fatiguer, the listeners exhibit threshold shifts approximately 8 dB greater than those at 1000 Hz (Figure 3). The threshold shifts produced by a 100 dB fatiguer are highly variable. Because of this and the few (4) listeners completed, it is unreasonable to consider the relation between TTS and fatigue at 2000 Hz until the remainder of the data is acquired. However, we expect that in the 2000 Hz region we are seeing effects of external ear resonance (cf. Shaw, 1974).

Octave-band noise with center frequencies equal to the pure-tone exposure frequencies generally produce less fatigue than their pure-tone counterparts although power was constant. As can be seen in Figure 4, this difference is approximately 5 dB. The trend is more consistent at the higher fatigue levels. At lower fatiguing exposures, the low level of fatigue effectively reduces the trend. It would appear then that because the distortion is predictive of pure-tone TTS, it is similarly predictive of octave-band noise induced TTS.

B. Smoking Effects

As an initial examination of the influence of smoking on TTS susceptibility, we exposed smokers and non-smokers to fatiguing tones at 1 K Hz and 2 K Hz at 95 dB SPL and to 2 K Hz at 90 dB SPL. We examined the effects of smoking on TTS, on threshold, and the relation between TTS and threshold. In Figure 5 we plot TTS against threshold for each of the groups. The conditions of the measurements were 1000 Hz fatigue and a 1400 Hz test. Clearly there is no difference in pre-fatigue threshold between the smoking and the non-smoking group. All thresholds in this selected "normal hearing" group ranged between -3 dB SPL and 16 dB SPL (-13.5 to +5.5 dB HTL) with an additional listener down at -14 dB SPL.

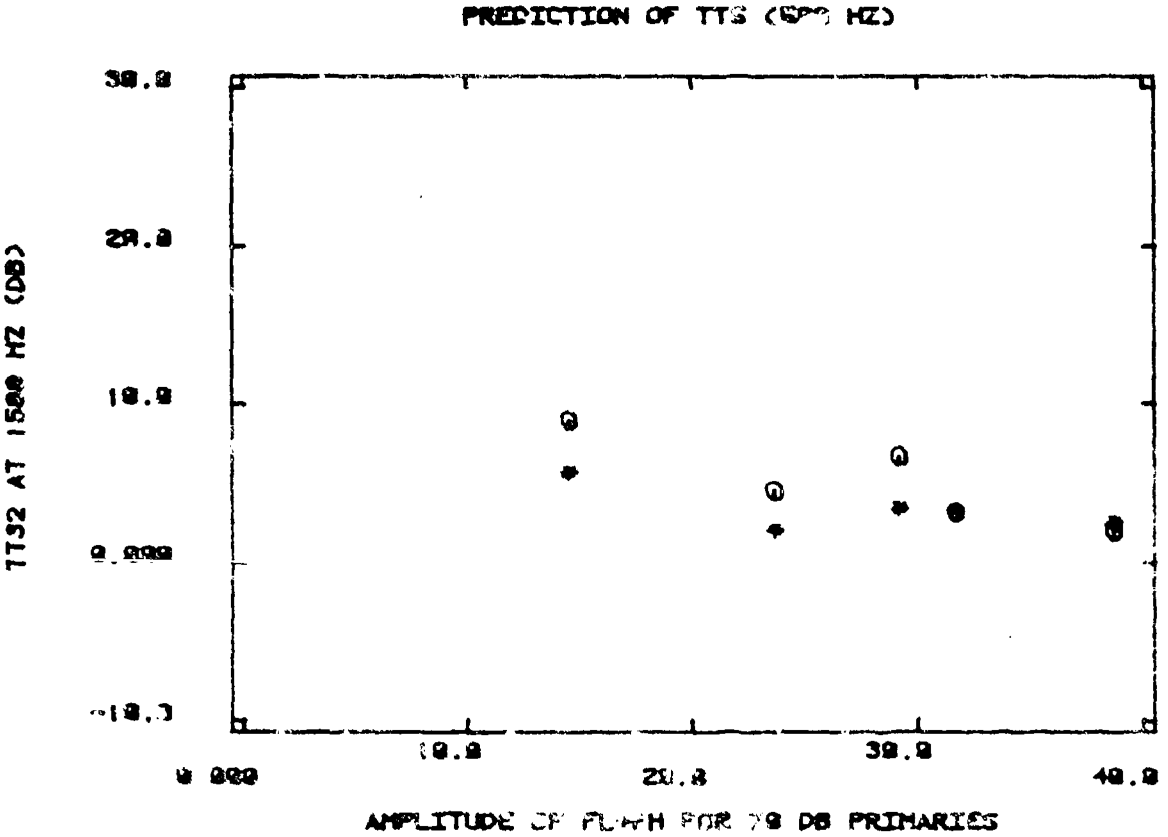

Figure 2: Relationship between TTS_2 and aural nonlinearity. 500Hz exposure.

* 90 dB SPL fatiguer

Q 100 dB SPL fatiguer

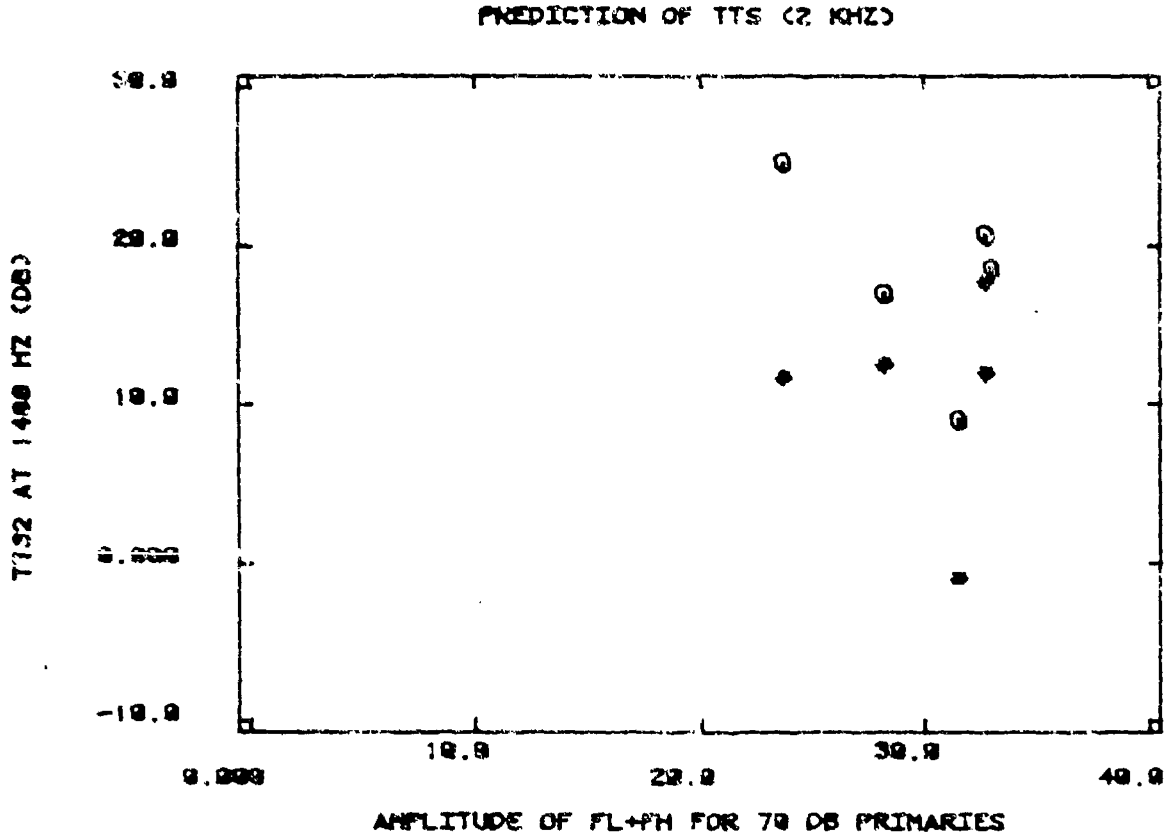

Figure 3: Relation between aural nonlinearity and TTS_2. 2000Hz exposure.

*90 dB SPL fatiguer

Ⓠ 100 dB SPL fatiguer

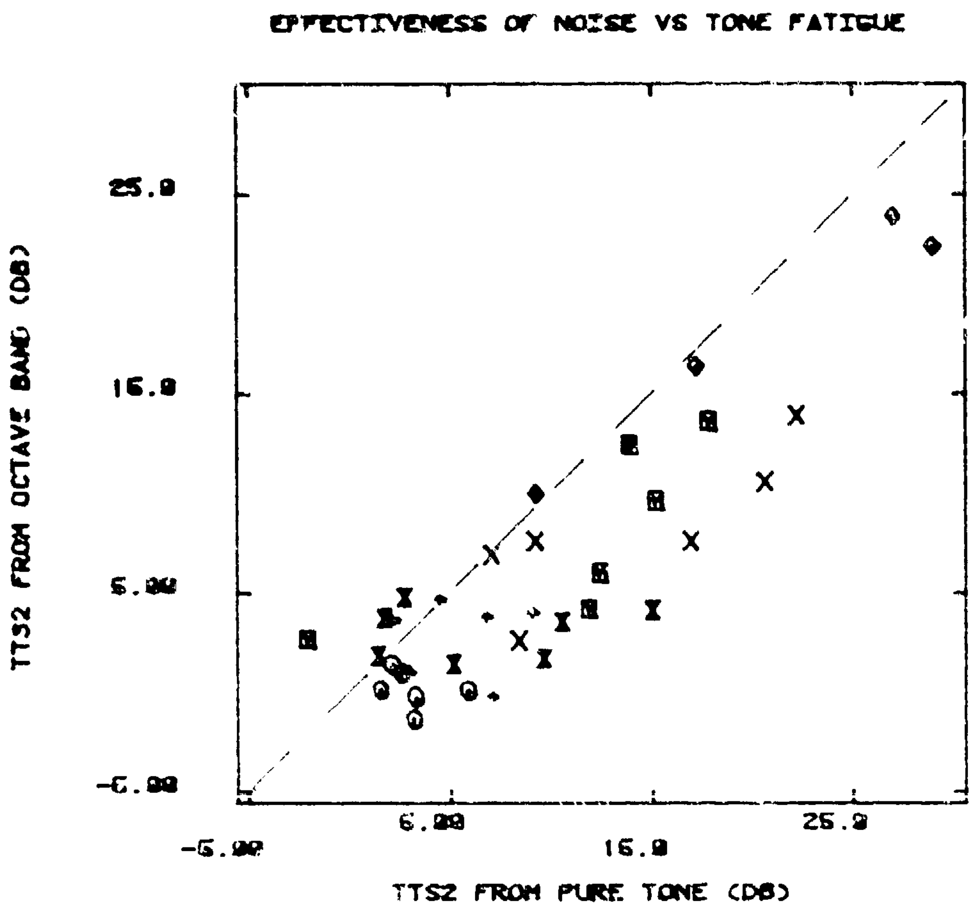

Figure 4: Comparison of TTS_2 for pure-tone and equal energy octave band exposures.

- 500 Hz @ 90 dB
- 500 Hz @ 100 dB
- 1000 Hz @ 90 dB
- 1000 Hz @ 100 dB
- 2000 Hz @ 90 dB
- 2000 Hz @ 100 dB

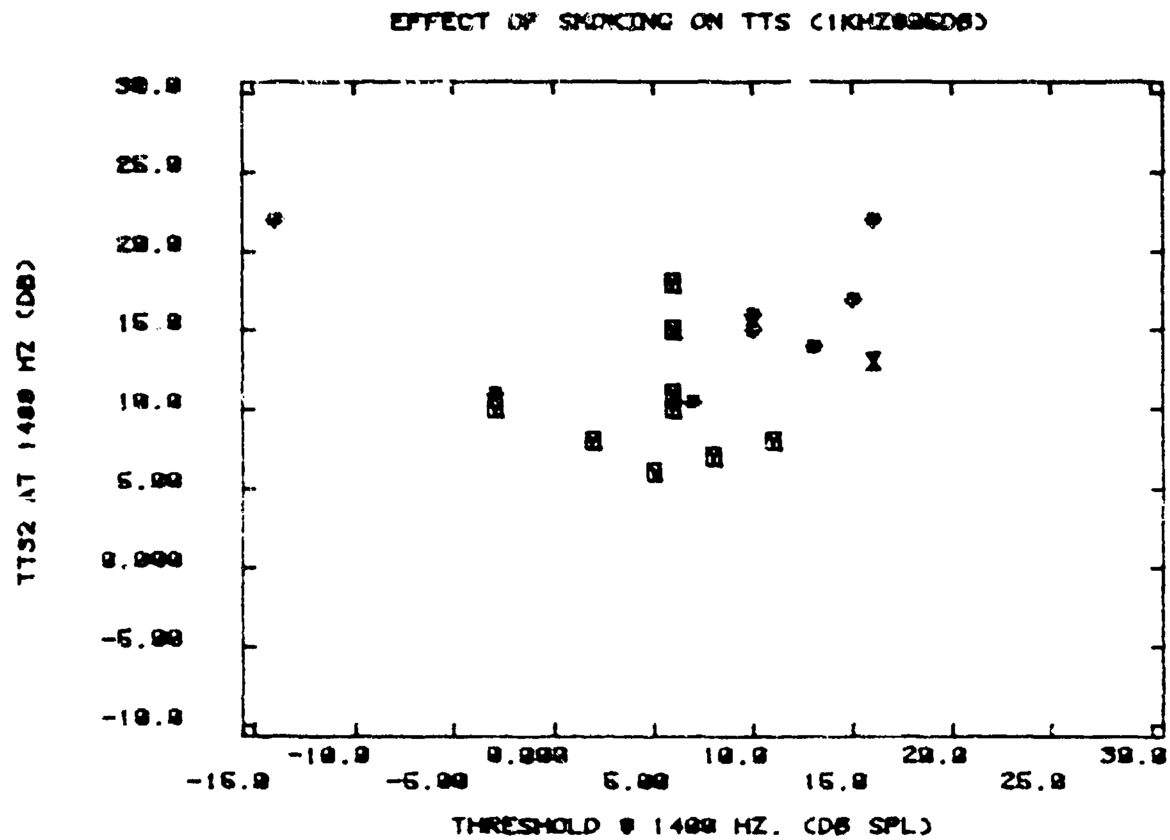

Figure 5: Pre-fatigue thresholds and TTS_2 for 1000 Hz fatigue and 1400 Hz test.

*Smokers
Y Non-smokers
X THC User

Threshold at the test frequency also is unrelated to the TTS_2 produced by the 95 dB fatiguing tone. This is well illustrated by the fact that the listener with the -14 dB SPL threshold and the listener with the +16 dB SPL threshold experienced identical TTS_2s of 22 dB. Further examination shows that the TTS_2 tends to fall in two ranges: from 14-22 dB of threshold shift there are seven smokers and two non-smokers. In the lower range from 6-11 dB of threshold shift, there are data from seven non-smokers and two smokers.

One subject, who professed to be a non-smoker, fell between the two ranges at 12 dB TTS . Because of other irregularities in his data he was questioned further about his smoking habits at which time he admitted that he was, indeed, not a tobacco smoker but that did not preclude his chronic smoking of other non-tobacco substances.

At 1000 Hz, it would appear that there is a sensitization to TTS proc ed by regular use of tobacco. Caution is advised in applying undue quantification o these data, however, because the amount of tobacco usage was not controlled. Listeners were only asked about their general smoking habits. All listeners in the smoking category were 1/2 to 1 pack (20 cigarettes) per day users. Furthermore, we did not control for the time over which the cigarettes were used. This may influence TTS susceptibility.

One listener was exposed to noise before and after abstainence from smoking. His two tracings illustrate the difference between the post-fatigue threshold and pre-fatigue threshold as a function of recovery time (fig. 6). In the upper tracing, the listener had been smoking prior to the test session. He exhibits a large initial threshold shift followed by recovery, desensitizaiton, and some further recovery. On another day, the same fatigue and test conditions were repeated. The only difference was that the subject had not smoked since the previous evening. His threshold shift following fatigue for this "non-smoking trial" is shown by the lower curve. Here he starts with about 2 dB of TTS at 20 seconds compared with 36 dB of TTS in the upper trace. After a short time (100 sec) he exhibits no TTS. The effect is regrettable on this individual.

Although it is obviously dangerous to generalize on the basis of one listener, these results would suggest that the effect of smoking on TTS susceptibility is reversible over a short period.

Comparisons of threshold and TTS at 2000 Hz suffer from the same variability as do the other 2000 Hz fatiguing measures. With 90 dB SPL fatiguer, there may be a trend to higher TTS for the smoking group (fig. 7).

However, with a 95 dB SPL fatiguer this is not supported (fig. 8). As exposure frequency increases, TTS also increases. The 95 dB exposure therefore may be of great enough intensity to mask the differences between smokers and non-smokers.

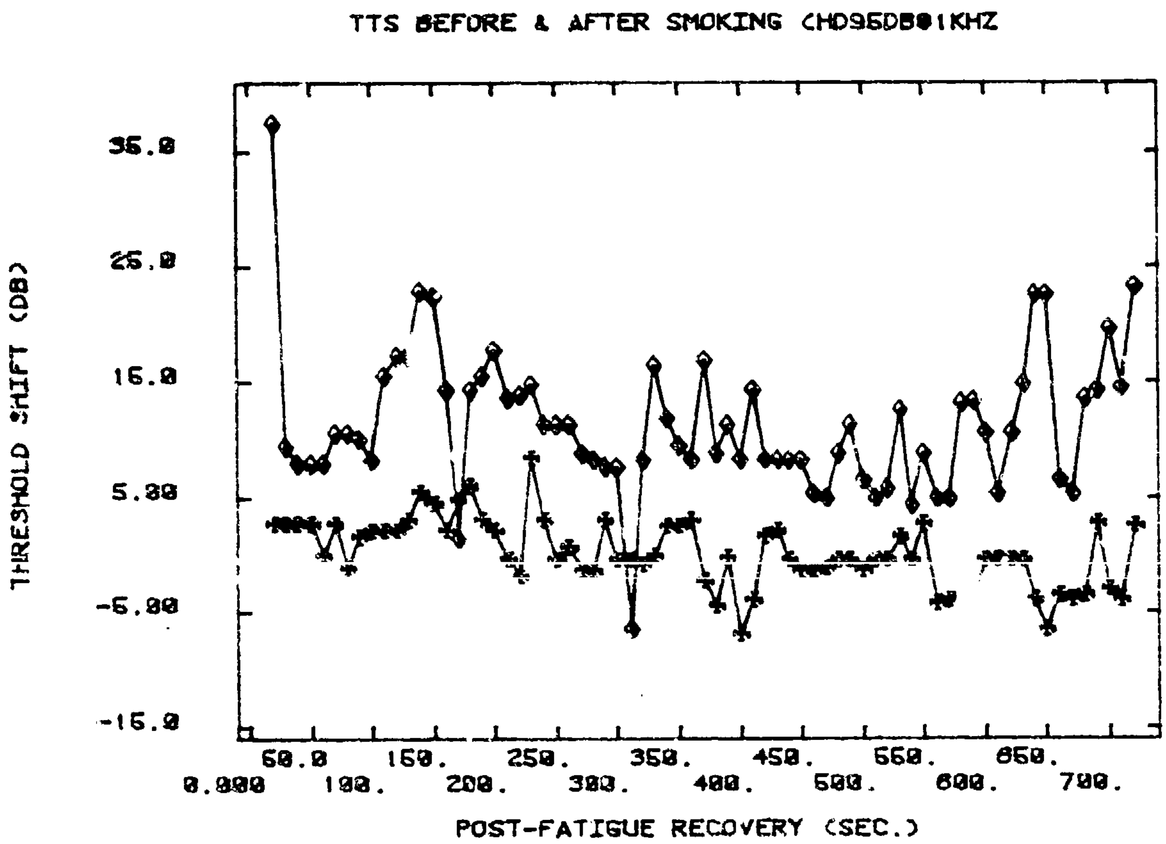

Figure 6: TTS following exposure to 95 dB SPL 1KHz fatiguer for 12 minutes.

◇ 4 hours after smoking
+ 12 hours after smoking

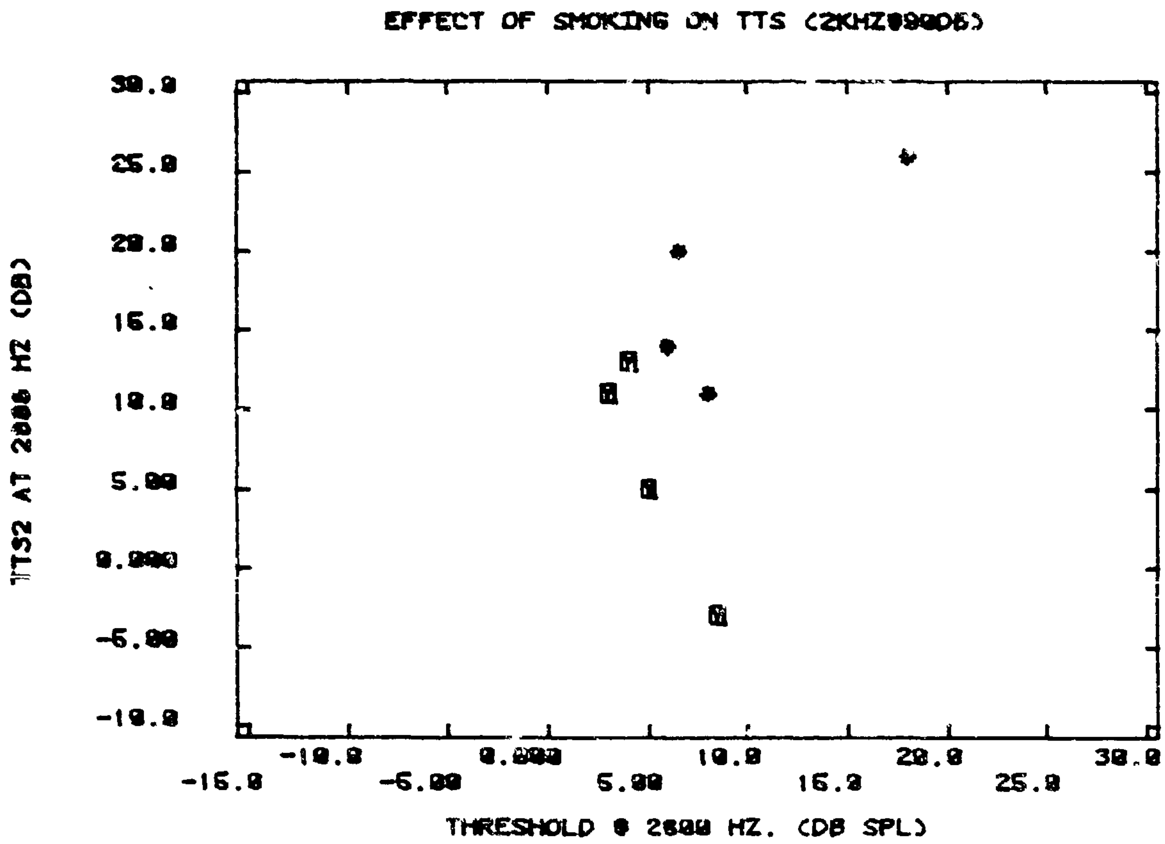

Figure 7: Pre-fatigue thresholds and TTS_2. 2KHz exposure 90 dB SPL.

* Smokers
Non-smokers

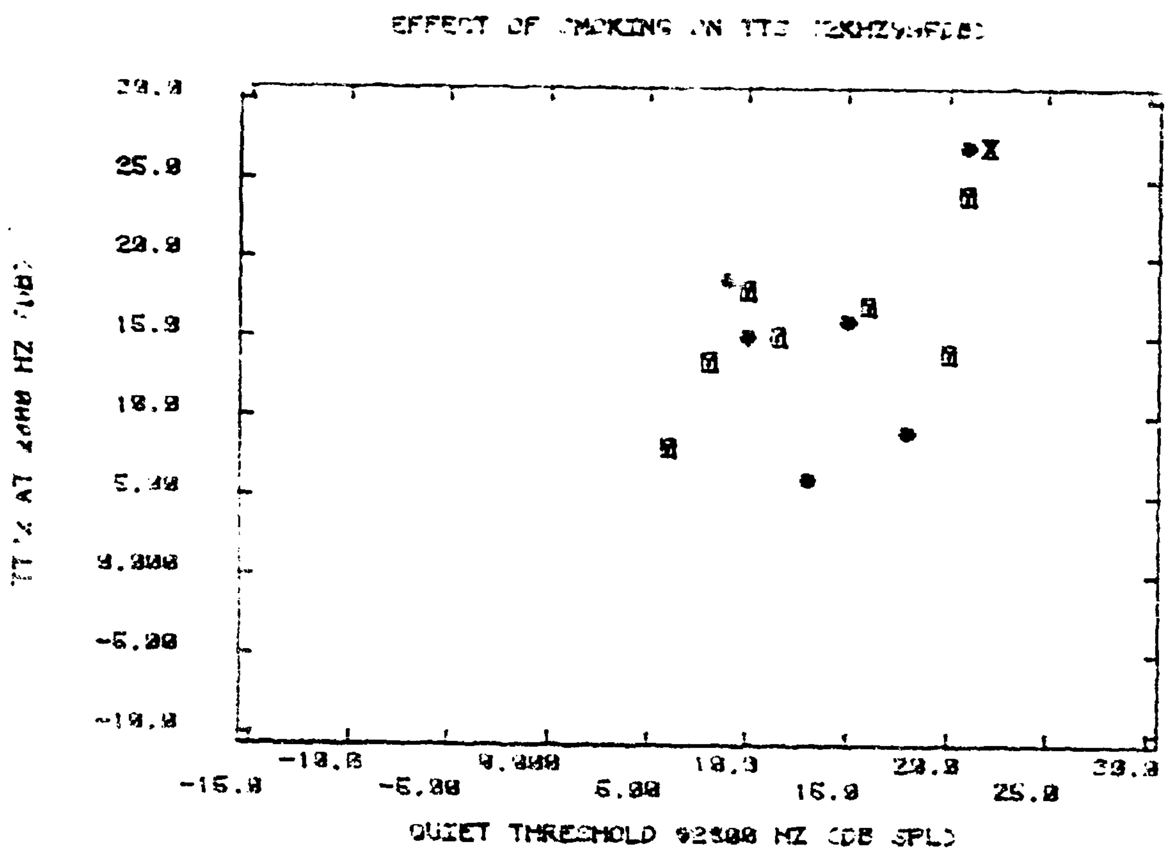

Figure 8: Pre-fatigue thresholds and TTS_2. 2KHz exposure 95 dB SPL.

* Smokers

◘ Non-smokers

VI. SUMMARY OF PROGRESS TO DATE

Factors Determining Susceptibility to Noise Induced Threshold Shift

The initial hypothesis of this study, that there is a mechanical factor which may predispose an ear to fatigue, must be modified to recognize and possibly control for, other physiological contributors to overall TTS sensitivity. Mechanical factors may exist and may be quantifiable; but the physiological factors may be as easy or easier to assess and may in fact be controllable.

Analysis of the data presented here indicates that measurement of TTS at low frequencies is of marginal utility when evaluating the relation between aural overload and TTS susceptibility. This, because threshold shifts at 500 Hz in response to fatiguing levels used in the study are minimal. The variability in the 2000 Hz data is more troublesome.

One explanation of the variability, as yet untested, is that we are operating in the region of the natural resonance of the acoustic transmission pathway (Shaw. 1974). For those listeners for whom the fatigue frequency is close to their resonant frequency, there is an increase in sound pressure at the tympanic membrane. For those for whom the resonant frequency is farther from the fatigue of frequency there is no pressure gain and hence less fatiguing input.

The 1000 Hz data supports the relation found in our pilot study (Cobb and Erdreich, 1976). Following completion of our data acquisition we will be in a position to evaluate the variability in the relationship and to determine its applicability to large population screening.

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